REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE:	3. REPORT TYPE AND DATES COVERED Final Report 1-May-2000 - 31-Oct-2005

4. TITLE AND SUBTITLE
Quantum Information Technology: Entanglement, Teleportation, and Memory

5. FUNDING NUMBERS
DAAD190010177

6. AUTHORS
Jeffrey H. Shapiro

8. PERFORMING ORGANIZATION REPORT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Massachusetts Institute of Technology
Office of Sponsored Programs
Bldg. E19-750
Cambridge, MA 02139 -4307

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

41052-PH-MUR.11

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12. DISTRIBUTION AVAILIBILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for Public Release; Distribution Unlimited	

13. ABSTRACT (Maximum 200 words)

The abstract is below since many authors do not follow the 200 word limit

14. SUBJECT TERMS
quantum communication, teleportation, entanglement, quantum memory, quantum logic gates

15. NUMBER OF PAGES
Unknown due to possible attachments

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev .2-89)
Prescribed by ANSI Std.
239-18 298-102

Report Title

Quantum Information Technology: Entanglement, Teleportation, and Memory

ABSTRACT

A team of researchers from the Massachusetts Institute of Technology and Northwestern University worked to develop the technology elements needed to perform long-distance, high-fidelity qubit teleportation. In particular: this team developed novel sources of polarization-entangled photons based on chi-2 and chi-3 materials; it developed devices for high-efficiency quantum state frequency conversion and demonstrated long-distance entanglement distribution via optical fiber; and it worked toward realizing quantum memory elements in both trapped-atom and atomic-ensemble systems. The experimental work was supported by a variety of theoretical studies. Other theoretical work addressed more general issues in quantum communication and entanglement applications.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

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Number of Papers published in peer-reviewed journals: 87.00

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J. H. Shapiro, " Architectures for long-distance quantum communication ," in Proc. Seventh International Conference on Squeezed States and Uncertainty Relations, Boston, June 2001.

J.H. Shapiro, J. Aung, and B.J. Yen, "Quantum error models and error mitigation for long-distance teleportation architectures," in Proceedings of the Feynman Festival (2002), quant-ph/0211086.

J.H. Shapiro, "Quantum Gaussian noise," Proc. SPIE, vol. 5111, pp. 382-395 (2003).

J.H. Shapiro, "Generating quantum interference and polarization entanglement with optical parametric amplifiers," in Proceedings of the Sixth International Conference on Quantum Communication, Measurement and Computing , J.H. Shapiro and O. Hirota, eds. (Rinton Press, Princeton, 2003).

S. Lloyd, "Entanglement and channel capacity," in Proceedings of the Sixth International Conference on Quantum Communication, Measurement and Computing , J.H. Shapiro and O. Hirota, eds. (Rinton Press, Princeton, 2003).

V. Giovannetti, S. Guha, S. Lloyd, L. Maccone, J. H. Shapiro, and B. J. Yen, "Minimum Bosonic Channels Output Entropies", in Proceedings of the 7th International Conference on Quantum Communication, Measurement, and Computing, AIP Conference Proceedings Vol. 734 (American Institute of Physics, Melville, New York, 2004).

V. Giovannetti, S. Lloyd, and L. Maccone, "Quantum positioning system", in Proceedings of the 8th Rochester Conference on Coherence and Quantum Optics, N. P. Bigelow, J. H. Eberly, C. R. Stroud, and I. A. Walmsley eds. (Kluwer Academic, New York, 2003).

J. H. Shapiro, V. Giovannetti, S. Guha, S. Lloyd, L. Maccone, and B. J. Yen, "Capacity of Bosonic Communications", in Proceedings of the 7th International Conference on Quantum Communication, Measurement, and Computing, AIP Conference Proceedings Vol. 734 (American Institute of Physics, Melville, New York, 2004).

B. J. Yen and J. H. Shapiro "Two problems in multiple access quantum communication," in Proceedings of the 7th International Conference on Quantum Communication, Measurement, and Computing, AIP Conference Proceedings Vol. 734 (American Institute of Physics, Melville, New York, 2004).

Shapiro, J.H., "Quantum Theory of Coincidence Counting: Gaussian States and Quantum Interference," Presented at the 2004 Annual Meeting, Opt. Soc. Am., October 2004. Rochester, NY.

Razavi, M., and Shapiro, J.H., "Long-Distance Quantum Communication with Neutral Atoms," Presented at the SPIE Conference on Fluctuations and Noise in Photonics and Quantum Optics, Austin, TX. (Proc. SPIE, 5842, 2005, pp. 132–143.)

Yen, B.J., and Shapiro, J.H., "Multiple-Access Bosonic Communications," Presented at the SPIE Conference on Fluctuations and Noise in Photonics and Quantum Optics, Austin, TX. (Proc. SPIE, 5842, 2005, pp. 93–104.)

J.H. Shapiro, B.J. Yen, S. Guha, and B.I. Erkmen, "Classical Communication in the Presence of Quantum Gaussian Noise," Proc. SPIE

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H.P. Yuen, "Why there is no impossibility theorem on secure quantum bit commitment," in Proceedings of the Sixth International Conference on Quantum Communication, Measurement and Computing , J.H. Shapiro and O. Hirota, eds. (Rinton Press, Princeton, 2003).

M. Raginsky, "Entropy-energy balance in noisy quantum computers," in Proceedings of the Sixth International Conference on Quantum Communication, Measurement and Computing, J.H. Shapiro and O. Hirota, eds. (Rinton Press, Princeton, 2003).

H. P. Yuen, " Anonymous key quantum cryptography and unconditionally secure quantum bit commitment, " in Quantum Communication, Measurement, and Computing 3 , O. Hirota and P. Tombesi, eds., (Kluwer , New York , 2001).

Number of Papers published in non peer-reviewed journals: 55.00

(c) Papers presented at meetings, but not published in conference proceedings (N/A for none)

P. Kumar, P. L. Voss, X. Li, K. F. Lee, J. Chen, C. Liang, P. Devgan, R. Tang, and V. S. Grigoryan, "Parametric processes in fibers for quantum and classical communications applications," invited paper presented at the International Conference on Quantum Electronics 2005 and the Pacific Rim Conference on Lasers and Electro-Optics 2005 (IQEC/CLEO-PR'05), Toshi Center Kaikan, Tokyo, Japan, July 11-15, 2005; paper CFJ3-1-INV.

P. Kumar, K. F. Lee, J. Chen, X. Li, and P. L. Voss, "Quantum Information Processing with Optical Fibers," invited paper presented at the Quantum Electronics and Laser Science Conference (QELS'2005), Baltimore, MD, May 22-27, 2005; paper QTuJ1.

S. W. Dugan, X. Li, P. L. Voss, and P. Kumar, "Frequency up-conversion at the single-photon level in a PPLN waveguide," presented at the Quantum Electronics and Laser Science Conference (QELS'2005), Baltimore, MD, May 22-27, 2005; paper QThJ2.

X. Li, P. L. Voss, J. Chen, K. F. Lee, and P. Kumar, "Measurement of co- and cross-polarized Raman spectra in silica fiber for small detunings," presented at the Conference on Lasers and Electro-Optics (CLEO'2005), Baltimore, MD, May 22-27, 2005; paper CThB6.

P. Kumar, K. F. Lee, J. Chen, X. Li, and P. L. Voss, "Quantum information processing with optical fibers," invited paper presented at the 9th International Conference on Squeezed States and Uncertainty Relations (ICSSUR'05), Besançon, France, May 2-6, 2005; paper I-37.

P. Kumar, X. Li, J. Chen, and P. L. Voss, "Telecom-Band Entanglement Generation and Distribution in Standard Fibers," invited paper presented at the conference on Quantum Optics and Applications in Computing and Communications, Beijing, China, November 8-12, 2004 as part of Photonics Asia.

P. L. Voss, R. Tang, J. Lasri, P. Devgan, and P. Kumar, "Noise limits in fiber optical parametric amplification and wavelength conversion," invited paper presented at the SPIE International Symposium on Information Technologies and Communications (ITCom 2004)--Conference on Active and Passive Optical Components for WDM Communications IV (Conference 5595), Pennsylvania Convention Center, Philadelphia, Pennsylvania, October 25-28, 2004; paper 5595-05.

G. C. Cardoso, G. S. Pati, V. Gopal, A. Heifetz, M. S. Shahriar, and P. Kumar, "Single-photon Raman gain for single-photon detection," presented at the Frontiers in Optics--Annual meeting of the Optical Society of America, Rochester, NY, October 10-14, 2004; paper LMC4.

P. Kumar, "Long-distance distribution of fiber-generated entanglement," invited paper presented at the 2nd Feynman Festival, University of Maryland, College Park, MD, August 20-25, 2004.

P. Kumar, "Telecom-Band Entanglement Generation, Storage, and Long-Distances Distribution," invited paper presented at the conference on Nonlinear Optics: Materials, Fundamentals and Applications, Waikoloa Beach Marriott, Waikoloa, Hawaii, August 2-6, 2004; paper FA1.

J. Chen, X. Li, and P. Kumar, "Quantum Theory for Two-Photon-State Generation by Means of Four-Wave Mixing in Optical Fiber," invited paper presented at the SPIE 2004 Annual Meeting: Conference on Quantum Communications and Quantum Imaging II (Conference 5551), Denver, CO, August 2-6, 2004; paper 5551-21.

P. Kumar, "Practical Quantum Communication and Cryptography for WDM Optical Networks," QCM Award Paper presented at the 7th International Conference on Quantum Communication, Measurement, and Computing (QCM&C'04), University of Strathclyde, Glasgow, Scotland, U.K., July 25-29, 2004.

P. Kumar, X. Li, P. Voss, J. Chen, S. Dugan, "Fiber-optic quantum communication," invited paper presented at the 1st Great Lakes Photonics Symposium, Conference on Quantum Optics and Advanced Spectroscopy, Cleveland, OH, June 8-9, 2004.

P. L. Voss and P. Kumar, "Raman-effect induced noise-figure limit for \chi(3) parametric amplifiers and wavelength converters," presented at the Optical Fiber Communications Conference (OFC'2004), Los Angeles Convention Center, Los Angeles, CA, February 22-27, 2004; paper TuK4.

P. Voss, X. Li, R. Tang, J. Sharping, and P. Kumar, "Raman-induced limits on applications of fiber parametric amplifiers," presented at the 34th Winter Colloquium on the Physics of Quantum Electronics, Snowbird, Utah, January 4-8, 2004.

X. Li, P. Voss, J. E. Sharping, J. Chen, and P. Kumar, "Generation and distribution of quantum entanglement in the telecom band with standard optical fiber," presented at the 2003 Optical Society of America Annual Meeting, Tucson, AZ, October 5-9, 2003; paper WAA4. See the Annual Meeting Program Digest, (Optical Society of America, Washington, D.C. 2003).

P. L. Voss, K. G. Köprülü, S.-K. Choi, S. Dugan, and P. Kumar, "Room temperature high speed InGaAs/InP avalanche photodiode single photon counters," presented at the 2003 Optical Society of America Annual Meeting, Tucson, AZ, October 5-9, 2003; paper WAA1. See the Annual Meeting Program Digest, (Optical Society of America, Washington, D.C. 2003).

J. H. Shapiro, F. N. C. Wong, P. Kumar, and S. M. Shahriar, "Progress toward long-distance, high-fidelity quantum communication," invited paper presented at the 2003 Optical Society of America Annual Meeting, Tucson, AZ, October 5-9, 2003; paper ThKK3. See the Annual Meeting Program Digest, (Optical Society of America, Washington, D.C. 2003).

P. Kumar, X. Li, P. L. Voss, J. E. Sharping, and J. Chen, "Devices for Optical Fiber Quantum Communications," invited paper presented at ITCom 2003--SPIE International Symposium on Information Technologies and Communications--Conference on Semiconductor Optoelectronic Devices for Lightwave Communication (Conference 5248), September 8-10, 2003, Orlando, FL; paper 5248-01.

P. Kumar, "Fiber-Optic Quantum Communication," invited paper presented at the 8th International Conference on Squeezed States and Uncertainty Relations (ICSSUR'2003), Puebla, Mexico, June 9-13, 2003.

X. Li, P. Voss, J E. Sharping, and P. Kumar, "Violation of Bell's inequality near 1550 nm using an all-fiber source of polarization-entangled photon pairs," presented at the Quantum Electronics and Laser Science Conference (QELS'2003), Baltimore, MD, June 1-6, 2003; paper QTuB4. See QELS'03 Technical Digest (Optical Society of America, Washington, D.C. 2003).

P. Voss and P. Kumar, "Room temperature IR InGaAs/InP APD photon counters for quantum optics experiments," invited paper presented at the Workshop on Single Photon: Detectors, Applications, and Measurement Methods, held at the National Institute of Standards and Technology (NIST), Gaithersburg, MD, March 31 - April 1, 2003. The workshop was sponsored by NIST and ARDA.

X. Li, M. Fiorentino, P. L. Voss, J. E. Sharping, G. A. Barbosa, and P. Kumar, "All-fiber photon-pair source for quantum communications," presented at the 2002 Optical Society of America Annual Meeting, Orlando, FL, September 29-October 4, 2002; paper ThG1. See p. 123 of the 2002 Annual Meeting Program Digest, (Optical Society of America, Washington, D.C. 2002).

X. Li, P. L. Voss, J. E. Sharping, M. Fiorentino, and P. Kumar, "An all-fiber source of polarization-entangled photon pairs in the 1550 nm telecom band," presented as a postdeadline paper at the Conference on Nonlinear Optics (NLO'2002) Maui, Hawaii, July 29-August 2, 2002.

P. Kumar, M. Fiorentino, J. E. Sharping, and P. L. Voss, "Fiber-optic sources for quantum communication," presented at the Conference on Nonlinear Optics (NLO'2002) Maui, Hawaii, July 29-August 2, 2002. See Trends in Optics and Photonics (TOPS), Vol. 79, Nonlinear Optics, OSA Technical Digest, Post-conference Edition, (Optical Society of America, Washington, D.C. 2002), pp. 28-30.

P. Kumar, "Fiber-Optic Sources of Quantum Entanglement," invited paper presented at the 6th International Conference on Quantum Communication, Measurement, and Computing (QCM&C'02) held at the MIT Campus, Cambridge, MA, July 22-26, 2002.

M. Fiorentino, P.L. Voss, X. Li, J. E. Sharping, G.A. Barbosa, and P. Kumar, "All-fiber photon-pair source for quantum communications," presented as a postdeadline paper at the 2002 Quantum Electronics and Laser Science Conference (QELS'02), Long Beach, CA, May 19-24, 2002; paper QPD4. See QELS'02 Post Conference Technical Digest (Optical Society of America, Washington, D.C., 2002).

J. E. Sharping, M. Fiorentino, P. Kumar, and R. S. Windeler "A microstructure-fiber based optical parametric oscillator," presented at the Conference on Lasers and Electro-Optics (CLEO'2002), Long Beach, CA, may 19-24, 2002; paper CtuB2. See CLEO'02 Technical Digest (Optical Society of America, Washington, D.C., 2002), pp. 141-142.

M. Fiorentino, J. E. Sharping, P. Kumar, and R. S. Windeler "Quantum solitons in microstructure fibers," presented at the IV Conference on Quantum Interferometry, ICTP, Trieste, Italy, March 11-15, 2002.

P. Kumar, "Fiber-optic quantum communications," invited paper presented at the 32nd Winter Colloquium on The Physics of Quantum Electronics, Snowbird, Utah, January 6-10, 2002.

J. E. Sharping, M Fiorentino, P. Kumar, and R. S. Windeler "Experimental nonlinear optics in microstructure fiber," presented at the 14th

Annual Meeting of the IEEE Lasers and Electro-Optics Society (LEOS'01), San Diego, CA, November 12-15, 2001, paper WV3. See pp. 572-573 of the LEOS'01 Conference Proceedings, (IEEE, Piscataway, N.J., 2001).

M. Fiorentino, P. Voss, J. E. Sharping and P. Kumar, "Fourth-order quantum interference at 1550 nm," presented at the 2001 Optical Society of America Annual Meeting, Long Beach, CA, October 14-19, 2001, paper ThF2. See p. 102 of the 2001 Annual Meeting Program Digest, (Optical Society of America, Washington, D.C., 2001).

J. E. Sharping, M. Fiorentino, P. Kumar, and R. S. Windeler, "Nonlinear fiber optics in microstructure fiber," presented at the 2001 Optical Society of America Annual Meeting, Long Beach, CA, October 14-19, 2001, paper ThF2. See p. 102 of the 2001 Annual Meeting Program Digest, (Optical Society of America, Washington, D.C., 2001).

P. Kumar, "Fiber generated quantum correlations for quantum-optical communications," invited paper presented at the Eighth Rochester Conference on Coherence and Quantum Optics, June 13-16, 2001, Campus of the University of Rochester, Rochester, N.Y. See Coherence and Quantum Optics VIII, Edited by N. P. Bigelow, J. H. Eberly, C. R. Stroud, and I. A. Walmsley, (Kluwer, New York, 2003), p. 185.

M. Fiorentino, J. E. Sharping, P. Kumar, A. Porzio, and R. S. Windeler, "Soliton squeezing in a microstructure fiber," invited paper presented at the 7th International Conference on Squeezed States and Uncertainty Relations (ICSSUR'2001), June 4-8, 2001, Boston, MA; see Conference Proceedings edited by D. Han, Y. S. Kim, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich (Online Publication), http://www.wam.umd.edu/ys/boston.html.

P. Kumar, "Quantum communication with fiber-optic devices," invited paper presented at the 2001 Quantum Electronics and Laser Science Conference (QELS'2001), Baltimore, MD, May 6-11, 2001; paper QThA2. See QELS'01 Technical Digest (Optical Society of America, Washington, D.C. 2001) p. 171.

J. E. Sharping, A. Coker, M. Fiorentino, P. Kumar, and R. S. Windeler, "Four-Wave Mixing in Microstructure Fiber," presented to the 2001 Conference on Lasers and Electro-Optics (CLEO'2001), Baltimore, MD, May 6-11, 2001; paper CThQ2. See CLEO '01 Technical Digest (Optical Society of America, Washington, D.C. 2001), p. 508.

M. Fiorentino, J. E. Sharping, P. Voss, P. Kumar, D. Levandovsky, and M. Vasilyev, "Soliton squeezing in asymmetric and symmetric fiber Mach-Zehnder nonlinear interferometers," presented to the 2001 Quantum Electronics and Laser Science Conference (QELS'2001), Baltimore, MD, May 6-11, 2001; paper QMC7. See QELS'01 Technical Digest (Optical Society of America, Washington, D.C. 2001).

M. Fiorentino, J. E. Sharping, D. Levandovsky, M. Vasilyev, and P. Kumar, "Soliton squeezing in a Mach-Zehnder fiber interferometer," presented as a post-deadline paper at the 2000 Optical Society of America Annual Meeting, Providence, RI, October 22-26, Paper PD5.

J. E. Sharping, M. Fiorentino, and P. Kumar, "Observation of twin-beams type quantum correlations in optical fiber," presented at the 2000 Optical Society of America Annual Meeting, Providence, RI, October 22-26, Paper WM2. See p. 99 of the 2000 Annual Meeting Program Digest, (Optical Society of America, Washington, D.C. 2000).

P. Kumar, "Quantum fiber-optics: Some recent experimental and theoretical developments," invited paper presented at the Nonlinear Optics: Materials, Fundamentals and Applications Topical Meeting (NLO'2000) held in Kauai-Lihue, HI, August 7-11, 2000; paper ThA6. See NLO'2000 pages 319-320.

“Ensemble-based Quantum Memory, Quantum Communication, and Quantum Computing,” Gour Pati, Kenneth Salit, Prem Kumar, and M.S. Shahriar, presented at the SPIE Photonics West Conference, San Jose, CA, January 2006 (invited).

“Slow- and Fast-Light Enhanced Rotation Sensing and Fabry-Perot Interferometry,” Renu Tripathi, Gour Pati, Venkatesh Gopal, Kenneth Salit, Mary Messal, M.S. Shahriar, presented at the SPIE Photonics West Conference, San Jose, CA, Jan 2006 (invited).

“Light-Shift Imbalance Induced Dipole Blockade for Deterministic Quantum Information Processing using Atomic Ensembles”, M.S. Shahriar, presented at the International Conference on Quantum Optics, Hong Kong, December, 2005 (invited)

“Slow-Light in Cold Atoms for Single Photon Detection,” M.S. Shahriar, Midwest Workshop on Cold Atoms, Urbana, IL, November, 2005 (invited)

“Observation of Slow-Light and Matched Dispersion in Sodium Vapor for Applications to Laub-Drag Enhanced Rotation Sensing,” Renu

Tripathi, Gour Pati, Mary Messall, Kenneth Salit, Venkatesh Gopal, Selim M. Shahriar, presented at the OSA Annual Meeting, Tucson, AZ, October, 2005.

“Slow and Superluminal Light Enhanced Ultrahigh Precision Optical Rotation Sensing,” Selim M. Shahriar, Gour Pati, Renu Tripathi, Venkatesh Gopal, Mary Messall, Kenneth Salit, presented at the OSA Annual Meeting, Tucson, AZ, October, 2005.

“Enhancement of Interferometric Precision Using Fast Light,” Selim M. Shahriar, Renu Tripathi, Gour Pati, Venkatesh Gopal, Kenneth Salit, Mary Messall, presented at the OSA Annual Meeting, Tucson, AZ, October, 2005.

“Solid State Quantum Computing Via Spectral Hole Burning,” M.S. Shahriar, presented at the International Workshop on Quantum Informatics, Dec 2004, Hong Kong (invited)

“Integrated Quantum Communication and Computing: The Quantum Internet,” M.S. Shahriar, presented at the International Workshop on Quantum Informatics, Dec 2004, Hong Kong (invited)

“Quantum Teleportation Using Neutral Atoms and Cavity-QED,” M.S. Shahriar, presented at the International Workshop on Quantum Informatics, Dec 2004, Hong Kong (invited)

“Pseudo-random noise in high-speed operation of quantum bits,” M.S. Shahriar, P. Pradhan, and J. Morzinski, presented at the Conference on Fluctuations and Noise in Photonics and Quantum Optics III, SPIE, Austin, Texas, 2005. (invited)

“Investigation towards realizing a slow-light based rotation sensor” G.S. Pati, R. Tripathi, P. Pradhan, R. Nair, V. Gopal, G. Cardoso, and M.S. Shahriar, presented at SPIE, Photonics West, 2005, San Jose, CA (invited)

“Effects of the Bloch-Siegert Oscillation on the Precision of Qubit Rotations: Direct Two-Level vs. Off-Resonant Raman Excitation,” P. Pradhan, G. Cardoso, J. Morzinski, and M.S. Shahriar, presented at the OSA Annual Meeting, Rochester, NY (2004)

“Single-Photon Raman Gain for Single-Photon Detection,” G. Cardoso, G.S. Pati, V. Gopal, A. Heifetz, M.S. Shahriar, and P. Kumar, presented at the OSA Annual Meeting, Rochester, NY (2004)

"Application of Slow-Light to Quantum Information Processing,” presented at the OSA Annual Meeting, Rochester, NY (2004) (Invited Paper).

"Photonic Bandgap Structures In NV-Diamond For Quantum Computing" R. Tripathi, J.K. Lee, and M.S. Shahriar, presented at the SPIE Photonics West, San Jose, CA (Jan., 2004) (Invited Paper).

“Quantum Communication and Computing Using Neutral Atoms,” M.S. Shahriar, presented at The Feynman Festival, University of Maryland (2004) (Invited Paper).

“Quantum communication via atomic-state teleportation for game theoretic applications,” M. S, Shahriar, presented at the Quantum Communications and Quantum Imaging II session of SPIE Annual Meeting, Denver, CO (August, 2004) (Invited Paper)

"Single Atom Interferometry and Its Application to Generation of Motional Entanglement," M.S. Shahriar, A. Heifetz, K. Salit, G. Pati, and V. Gopal, presented at Progress in Quantum Electronics, Snowbird, Utah (January 2004) (Invited Paper).

"Atomic Ensemble Quantum Memory Using Rb Vapor for Quantum Entanglement and Teleportation," G. Cardoso, A. Heifetz, V. Gopal, G.S. Pati, and M.S. Shahriar, presented at the SPIE Photonics West, San Jose, CA (Jan., 2004) (Invited Paper).

"Observation of the Phase Of a Microwave Field via the Bloch-Siegert Oscillation," G. Cardoso, P. Pradhan, and M.S. Shahriar, the OSA Annual Meeting, Tucson, Az (October 2003) (Postdeadline Paper)

"Strongly Pump-Suppressed Raman Gain in 85Rb for Generation of Macroscopic Entanglement of Vapor Cells," A. Agarwal, A. Heifetz, A. Agarwal, A. Heifetz, G. Cardoso, V. Gopal, P. Kumar, and M.S. Shahriar, presented at the Progress In Electromagnetic Research Symposium 2003, Honolulu, HI, (October 2003) (Invited Paper).

“Observation of the Phase Of a Microwave Field Using Single-Atom Nonlinear Optics," G. Cardoso, P. Pradhan, and M.S. Shahriar, presented at the Progress In Electromagnetic Research Symposium 2003, Honolulu, HI, (October 2003) (Invited Paper)

"Progress toward long-distance, high-fidelity quantum communication," N.C. Wong, P. Kumar, M.S. Shahriar, and Jeffrey Shapiro, presented at the OSA Annual Meeting, Tucson, AZ (October 2003) (Invited Paper).

“Measurement and Teleportation of The Phase of An Electromagnetic Field via Flourescence Detection,” M.S. Shahriar, P.Pradhan, and J. Morzinski, presented at the Annual Meeting of the Optical Society of America, Orlando, FL (2002).

"Determination and Teleportation Of The Phase Of An Electromagnetic Field Via Incoherent Detection Of Fluorescence," M. S. Shahriar and P. Pradhan, presented at the APS Annual Meeting, March 2002.

“Teleportation of Atomic States via Complete Measurement of Bell States” V. Gopal, J. Morzinsky, and M.S. Shahriar, presented at the Progress In Electromagnetic Research Symposium 2002, Cambridge, MA (July 2002)

“Determination of the Phase of an Electromagnetic Field via Incoherent Detection of Fluorescence using the Bloch-Siegert Oscillation,” P. Pradhan, J. Morzinsky and M.S. Shahriar, presented at the Progress In Electromagnetic Research Symposium 2002, Cambridge, MA (July 2002)

“Quantum Computing using NV-Diamond,” M.S. Shahriar and P.R. Hemmer, presented at the Progress in Quantum Electronics conference, Snowbird, UT, Jan. 2002 (Invited).

“Applications of Slow and Stopped Light in Solid,” P.R. Hemmer and M.S. Shahriar, presented at the Progress in Quantum Electronics conference, Snowbird, UT, Jan. 2002 (Invited).

A.V. Turukhin, M.S. Shahriar, J.A. Musser, and P.R. Hemmer, “Spin Mediated Slowing and Stoppage of Light in a Solid,” presented at Spintech 1, Maui, Hawaii, 2001.

“Observation of Ultraslow Group Velocity of Light in a Pr:YSO crystal,” V.S. Sudarshanam, M.S. Shahriar, and P.R. Hemmer, 31st Winter Colloquium in Quantum Electronics, Snowbird, Utah, 2001.

F. König, E.J. Mason, M.A. Albota, and F.N.C. Wong, “Efficient source of tunable nondegenerate photon pairs at 800 nm and 1600 nm using periodically-poled lithium niobate,” presented at the 3rd European Quantum Information Processing and Communication Workshop, Dublin, Ireland, September 2002.

F.N.C Wong, “High-flux entanglement sources using periodically poled nonlinear materials,” presented at the Second Workshop on Quantum Cryptographic Applications, McLean, VA, February 2003.

M.A. Albota and F.N.C. Wong, “Single-photon detection at 1.55 _m with InGaAs avalanche photodiodes and via frequency upconversion,” presented at the Workshop on Single-Photon: Detectors, Applications, and Measurement Methods, Gaithersburg, MD, April 2003.

F. König, E.J. Mason, F.N.C. Wong, and M.A. Albota, “Efficient generation of polarization-entangled photon pairs at 795 and 1610 nm,” presented at the 4th European Quantum Information Processing and Communication Workshop, Oxford, United Kingdom, July 2003.

M.A. Albota, F.N.C. Wong, and J.H. Shapiro, “Entanglement generation, detection, and frequency conversion for quantum communication,” Cambridge-MIT Summer School, Belfast, Northern Ireland, September 2005.

J.H. Shapiro, “Capacity of Bosonic Communications,” Summer School on Quantum Information Theory and Technology, Cambridge-MIT Summer School, Belfast, Northern Ireland, September 2005.

S. Lloyd, “Quantum Communication,” Solvay Conference, Delphi, Greece, 2001.

S. Lloyd, “ Quantum Communication,” PIERS, Cambridge, MA, 2002.

S. Lloyd, “Quantum Communication Channels,” Nonextensive Statistical Mechanics Conference, Rio de Janeiro, Brazil, 2002

Number of Papers not Published: 82.00

(d) Manuscripts

M.A. Albota, F.N.C. Wong, and J.H. Shapiro, “Polarization-independent frequency conversion for quantum optical communication,” accepted for publication in J. Opt. Soc. Am. B, 2006.

P. L. Voss, K. G. Köprülü, and P. Kumar, “Raman-noise induced quantum limits for (3) nondegenerate phase-sensitive amplification and quadrature squeezing,” accepted for publication in Journal of the Optical Society of America B.; e-print quant-ph/0410214.

X. Li, C. Liang, K. F. Lee, J. Chen, P. L. Voss, and P. Kumar, "An integrable optical-fiber source of polarization entangled photon-pairs in the telecom band," submitted to Physical Review A; e-print quant-ph/0601087.

“Light-Shift Imbalance Induced Blockade of Collective Excitations Beyond the Lowest Order,” M.S. Shahriar, P. Pradhan, G.S. Pati, and K. Salit, submitted to Phys. Rev. Lett.

“Quantum Communication and Computing With Atomic Ensembles Using Light-Shift Imbalance Induced Blockade,” M.S. Shahriar, G.S. Pati, and K. Salit, submitted to Phys. Rev. Lett.

“A Magnetically Guided Atomic Fountain for Loading a Co-Centered Cavity-FORT System,” V. Gopal. K. Salit, G.S. Pati, and M.S. Shahriar, submitted to Review of Scientific Instruments.

“Multi-Spectral Characteristics of Raman Scattering under Gain Condition for Collective Excitation in Rubidium Atomic Vapor,” G.S. Pati, J. Vornehm, V. Gopal, G. Cardoso, P. Kumar, and M.S. Shahriar, submitted to Physical Review A.

“Ultrahigh Precision Absolute and Relative Rotation Sensing using Slow and Fast Light,” M.S. Shahriar, G.S. Pati, R. Tripathi, V. Gopal, and M. Messal, submitted to Phys. Rev. Lett.

“Enhancement of interferometric precision using fast light,” M.S. Shahriar, G.S. Pati, R. Tripathi, V. Gopal, and K. Salit, submitted to Phys. Rev. Lett.

“Suppression of the Bloch-Siegert Oscillation Induced Error in Qubit Rotations via the Use of Off-Resonance Raman Excitation,” K. Salit, P. Pradhan, G. Cardoso, J. Morzinski, and M.S. Shahriar , submitted to Optics Communications.

“Experimental Determination of the Degree of Enhancement in Laub-Drag Augmented Rotation Sensing using Slow-Light in Sodium Vapor,” R. Tripathi, G.S. Pati, M. Messall, K. Salit and M.S. Shahriar, submitted to Phys. Rev. A..

“Demonstration of Null Group Index For Ultra-high Enhancement of Fast-Light Assisted Rotation Sensing via Double Raman Gain in Rubidium Vapor,” G.S. Pati, R. Tripathi, M. Messall, K. Salit and M.S. Shahriar, submitted to Phys. Rev. A.

M. Razavi and J.H. Shapiro, "Long-Distance Quantum Communication with Neutral Atoms," submitted to Phys. Rev. A; e-print quant-ph/0512128.

Number of Manuscripts: 13.00

Number of Inventions:

Graduate Students

Jay Sharping (100%)
Paul Voss (50%)
Jun Chen (100%)
Sarah Dugan (100%)
Ayodeji Coker (33%)
Ying Tan 50%
Jacob Morzinski (100%)
Joseph Vornehm (100%)
Alexander Heifetz (50%)
Kenneth Salit (100%)
Jong-Kwon Lee (50%)
Adam Smith (50%)
Eser Keskiner (25%)
Maxim Raginsky (25%)
Ranjith Nair (25%)
Marius A. Albota (0%)
Taehyun Kim, (0%)
Christopher E. Kuklewicz (100%)
Onur Kuzucu (25%)
Elliott J. Mason (0%)
Joe Aung (100%)
Saikat Guha (100%)
Brent J. Yen (20%)
Ying Tan (75%)
Baris Erkmen (20%)
Rosalind Takat (25%)

Number of Graduate Students supported: 18.00

Total number of FTE graduate students: 14.00

Names of Post Doctorates

Marco Fiorentino (50%)
Friedrich. Koenig (30%)
Elliott J. Mason (0%)
Gaetan. Messin (0%)
Xiaoying Li (100%)
Jay Sharping (100%)
Paul Voss (50%)
Kim Fook Lee (33%)
Alex Turukhin (50%)
Venkatapuram Sudarshanam (50%)
Venkatesh Gopal (50%)
Gour Pati (50%)
Renu Tripathi (20%)
Prabhakar Pradhan (20%)
George Cardoso (50%)
Parminder Bhatia (50%)
Lorenzo Maccone (50%)
Vittorio Giovannetti (50%)

Number of Post Docs supported: 17.00

Total number of FTE Post Doctorates: 8.00

List of faculty supported by the grant that are National Academy Members

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Names of Faculty Supported

Jeffrey H. Shapiro
Prem Kumar
Selim M. Shahriar
Horace P. Yuen
Madhu Sudan
Peter L. Hagelstein
Seth Lloyd

Number of Faculty: 7.00

Names of Under Graduate students supported

Adil Gangat
Matthew Hall
Ning Li
Todd Levin
David Miller
Prem Gandhi
Mesfin Getaneh

Number of under graduate students: 7.00

Names of Personnel receiving masters degrees

Joseph Vornehm
Eser Keskiner
Emily Nelson
Joe Aung
Saikat Guha
Adam Smith
Ayodeji Coker

Number of Masters Awarded: 7.00

Names of personnel receiving PHDs

Ying Tan
Alexander Heifetz
Brent J. Yen
Christopher E. Kuklewicz
Elliott J. Mason
Jay E. Sharping
Paul Voss
Maxim Raginsky

Number of PHDs awarded: 8.00

Names of other research staff

Franco N. C. Wong

Sub Contractors (DD882)

1 a. Northwestern University

1 b. 633 Clark Street
Room G-547
Evanston IL 60208-1112

Sub Contractor Numbers (c): 5710001042, 571000408

Patent Clause Number (d-1): 37CFR401.14

Patent Date (d-2): 1/2/1980 12:00:00AM

Work Description (e): entangled photon generation in optical fiber; entangled photon distribution through optica

Sub Contract Award Date (f-1): 5/1/2000 12:00:00AM

Sub Contract Est Completion Date(f-2): 10/31/2005 12:00:00AM

Inventions (DD882)

5 **All-Fiber Photon-Pair Source for Quantum Communications**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Prem Kumar

5f-1a: Northwestern University

5f-c: 2145 North Sheridan Avenue
Evanston IL 60208

5a: Marco Fiorentino

5f-1a:

5f-c:

5a: Paul Voss

5f-1a:

5f-c:

5a: Jay E. Sharping

5f-1a:

5f-c:

Quantum Information Technology: Entanglement, Teleportation, and Quantum Memory

Research Summary

A team of researchers from the Massachusetts Institute of Technology (MIT) and Northwestern University (NU) worked to develop the technology elements needed to perform long-distance, high-fidelity qubit teleportation. In particular: this team developed novel sources of polarization-entangled photons based on $\chi^{(2)}$ and $\chi^{(3)}$ materials; it developed devices for high-efficiency quantum state frequency conversion and demonstrated long-distance entanglement distribution via optical fiber; and it worked toward realizing quantum memory elements in both trapped-atom and atomic-ensemble systems. The experimental work was supported by a variety of theoretical studies. Other theoretical work addressed more general issues in quantum communication and entanglement applications. This final report summarizes the major research accomplishment or our program. It begins with a review of the MIT/NU architecture for long-distance teleportation that was the basis for our program.

MIT/NU Qubit Teleportation Architecture

The MIT/NU architecture uses nonlinear optics to produce a stream of polarization-entangled photon pairs, i.e., signal and idler photon states of the singlet form

$$|\psi^-\rangle_{SI} \equiv (|HV\rangle_{SI} - |VH\rangle_{SI})/\sqrt{2}. \tag{1}$$

The signal and idler photons are routed down L-km-long lengths of standard telecommunication optical fiber—the signal photons proceeding down one fiber and the idler photons down the other—to a pair of quantum memories comprised of ^{87}Rb atoms that are trapped inside high-Q optical cavities [1]. One of these memories belongs to Alice and the other to Bob; the Bell-observable measurements are made in Alice's memory, and the teleportation-completing transformations are performed in Bob's memory. Without delving too much into details, see [2]–[5] for more information, the overall operation can be described in terms of architectural elements shown in Figs. 1–3.

Figure 1(a) shows a simplified energy diagram for the atomic levels in ^{87}Rb that are used in storing the signal and idler qubits from $|\psi^-\rangle_{SI}$ in Alice's memory and Bob's memory, respectively. A photon of arbitrary polarization—expressed as a mixture of left-circular and right-circular components (σ_- and σ_+, respectively) can be absorbed by a rubidium atom that is in the ground state A, transferring its coherence—the α and β values that together characterize its polarization state—to the energy-degenerate excited levels B. By coherently pumping the B-to-D transition with an appropriate laser field, this quantum coherence is transferred to long-lived D levels for storage and processing. Whether or not a photon has been captured in this manner can be verified—in a non-destructive manner—by subsequently pumping the A-to-C cycling transition with another laser field. If the atom has been transferred to the D states, then no fluorescence will be seen on this cycling transition. Thus, Alice and Bob run a time-slotted memory loading protocol in which they repeatedly try to absorb photons, starting over at the end of each trial in which one or both of them see cycling transition fluorescence [4]. By employing an appropriate lattice of such trapped atoms, Alice and Bob can sequentially accumulate a reservoir of shared entanglement for teleporting quantum states between their respective quantum computers.

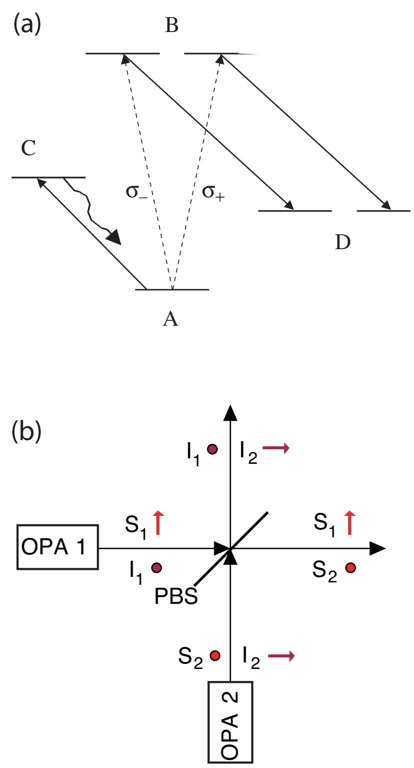

Figure 1: Essential components of the MIT/NU quantum communication architecture: (a) simplified energy-level diagram for the trapped rubidium atom; (b) source of polarization-entangled photon pairs.

Figure 1(b) sketches the structure of the entangled photon source in the MIT/NU architecture. It consists of two optical parametric amplifiers (OPAs), viz., resonant optical cavities each containing a second-order ($\chi^{(2)}$) nonlinear crystal in which photon pairs are produced whenever a photon from a strong pump laser of frequency ω_P fissions into a signal photon at frequency ω_S and an idler photon at frequency ω_I. Energy conservation, at the photon level, requires that $\omega_S + \omega_I = \omega_P$. Momentum conservation, at the photon level, requires that the wave vectors associated with the pump, signal, and idler obey $\vec{k}_S + \vec{k}_I = \vec{k}_P$. We assume type-II phase matching, in Fig. 1(b), which forces the signal and idler photons to be orthogonally polarized, as indicated by the bullets and arrows. With proper choice of nonlinear material, each OPA can be made to operate at frequency degeneracy, i.e., the center frequencies of the signal and idler will both be $\omega_P/2$. Making $\omega_P/2$ a cavity resonance for both the signal and the idler polarizations then dramatically increases the resulting signal-idler photon flux within the narrow (~15 MHz) bandwidth of the ^{87}Rb atomic line. Finally, by combining the outputs from two anti-phased, coherently-pumped OPAs on a polarizing beam splitter (PBS), we obtain the stream of polarization-entangled (singlet-state) photon pairs that are needed.

The ^{87}Rb-atom quantum memory has its A-to-B absorption line at 795 nm, but low-loss fiber propagation occurs in the 1.5-μm-wavelength window. Furthermore, standard telecommunication fiber does not preserve the polarization state of the light propagating through it. These obstacles to long-distance distribution of polarization-entangled photons to the Rb-atom memories are accounted for, within the MIT/NU architecture, by quantum-state frequency conversion [6] and time-division-multiplexed (TDM) polarization restoration (cf. [7]), as shown in Figs. 2 and 3. In particular, by

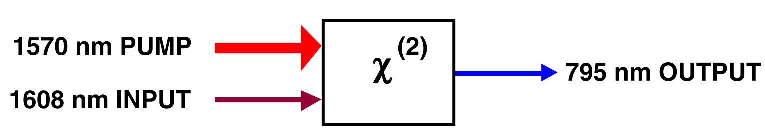

Figure 2: Schematic diagram of quantum-state frequency conversion.

applying a strong pump beam at 1570 nm to another second-order nonlinear crystal—chosen to satisfy the appropriate phase-matching condition—we can convert a qubit photon received at 1608 nm (in the low-loss fiber transmission window) to a qubit photon at the 795 nm wavelength of the ^{87}Rb quantum memory. For polarization restoration we postpone the PBS combining, shown in Fig. 1(b), until after fiber propagation. This is accomplished by transmitting time slices from the signal beams from our two OPAs down one fiber in the same linear polarization but in nonoverlapping time slots, accompanied by a strong out-of-band laser pulse. By tracking and restoring the linear polarization of the strong pulse, we can restore the linear polarization of the signal-beam time slices at the far end of the fiber. After this linear-polarization restoration, we then reassemble a time-epoch of the full vector signal beam by delaying the first time slot and combining it on a polarizing beam splitter with the second time slot after the latter has had its linear polarization rotated by 90°. A similar procedure is performed to reassemble idler time-slices after they have propagated down the other fiber.

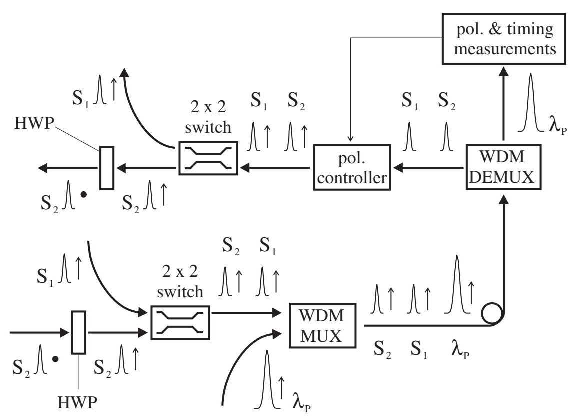

Figure 3: Schematic diagram of time-division-multiplexed polarization restoration for the signal beam. HWP = half-wave plate, WDM MUX = wavelength division multiplexer, WDM DEMUX = wavelength division demultiplexer.

Once Alice and Bob have entangled the atoms within their respective memories by absorbing an entangled pair of photons, the rest of the qubit teleportation protocol is accomplished as follows. Charlie's qubit message is stored in another ^{87}Rb atom, which is trapped in the same optical cavity as Alice's memory atom. By a coherence transfer procedure [8], Charlie inserts his qubit into Alice's memory atom in a manner that permits the Bell-observable measurement to be accomplished by determining in which of four possible states—not shown in Fig. 1(a)—that memory atom now resides. Alice sends the result of her Bell-observable measurement to Bob, who completes the teleportation process by standard atomic level manipulations that realize the phase-flip and bit-flip qubit operations. For details, see [3].

Architectural Analyses

MIT/NU Performance Analysis

During our program we have greatly refined our performance analysis for the MIT/NU qubit teleportation architecture. We first developed a complete cold-cavity treatment [5] that accounts for a wide variety of non-idealities that will be encountered in practice, such as imperfect polarization-restoration after fiber propagation, and pump-phase errors in the dual-OPA source. The cold-cavity work uses *ad hoc* lumped losses to account for coupling into the intra-cavity atoms. To fully assess the potential of the MIT/NU architecture, we began a hot-cavity treatment of its photon-atom interactions [11]. That work, although not yet complete, has already shown that photon-atom coupling may be far more forgiving of the photon's temporal mode structure than might have been guessed in advance. In particular, it is not necessary to employ a time-reversed version of the hot-cavity decay pulse in order to achieve single-atom coupling efficiencies in excess of 50%. The hot-cavity loading analysis is continuing in collaboration with researchers at Hewlett-Packard Laboratories.

Duan-Lukin-Cirac-Zoller Quantum Communication

Because of the experimental challenges in trapping single atoms in high-Q optical cavities—as is needed in the MIT/NU architecture—much excitement has been generated by proposals for distributing entanglement and performing teleportation between atomic ensembles in vapor cells by means of Raman scattering and photodetection (see below). We analyzed the Duan-Lukin-Cirac-Zoller (DLCZ) protocols for entanglement distribution and conditional teleportation within the same framework used for the cold-cavity analysis of the MIT/NU quantum communication architecture [9, 10]. This work has established the relative scaling behavior of these two approaches to long-distance quantum communication, and identified the DLCZ teleportation architecture's previously unreported need for photon-number resolving detectors. In collaboration with researchers from Hewlett-Packard Laboratories, we plan to address other configurations that have been proposed for ensemble-based quantum communication.

Entanglement Generation and Transmission

$\chi^{(2)}$ Sources

We have demonstrated a number of polarization-entanglement sources based on spontaneous parametric downconversion (SPDC) in periodically-poled $\chi^{(2)}$ crystals with collinear propagation geometry. These sources produced streams of entangled-photon-pair outputs with high flux and high quantum-interference visibility. Periodically-poled $KTiOPO_4$ (PPKTP) and periodically-poled $LiNbO_3$ (PPLN) were used to allow phase matching at convenient user-selected wavelengths. In one case PPKTP was used to generate outputs at 795 nm [12], matching the transition wavelength of ^{87}Rb

D_2 line associated with the MIT/NU architecture's trapped-atom quantum memory [3]. In another SPDC device, PPLN was used to generate nondegenerate outputs at 795 and 1609 nm [13], the latter can be sent through a single-mode telecommunication optical fiber for transport over long distances. Coupled into single-mode optical fibers, this PPLN source is spectrally bright with a generation rate of 300 pairs/s/mW of pump in 1 GHz of bandwidth.

Previous SPDC sources generally used angle phase-matching with cone-shaped outputs such that only a small fraction of the output flux could be collected. Moreover, they required significant spatial and spectral filtering. We showed that collinear propagation in which the pump and the two downconversion outputs co-propagate along the crystal allow one to collect most of the beam-like output light, resulting in much higher flux [12]. Moreover, we demonstrated a bidirectional-pumping geometry that eliminated the need for spatial, spectral, or temporal filtering [13, 14] in a compact device with high output flux. By using a polarization Sagnac interferometer to implement the bidirectional-pumping geometry, we demonstrated a phase-stable downconversion source that yields the highest flux in a bulk crystal system to date: 5,000 pairs/s/mW of pump in 1 nm of bandwidth at a quantum-interference visibility of 97% [15]. The Sagnac source of polarization entanglement can be utilized in a variety of quantum information processing tasks requiring both high flux and high entanglement purity.

By inserting the nonlinear crystal inside an optical cavity, we modified our downconversion outputs by the signal and idler double-resonance of the cavity obtaining a comb of narrowband outputs of polarization-entangled photons [16], fulfilling the original vision of a dual-OPA entanglement source [2]. The source output thus obtained exhibited collapses and revivals of the Hong-Ou-Mandel two-photon quantum-interference dips. This source can be filtered by an external optical cavity to yield polarization-entangled photons with a narrow bandwidth of ~25 MHz, with an estimated flux of ~1 pair/s/mW of pump in 1 MHz, which is currently the highest spectral brightness of all entanglement sources. This source is suitable for loading quantum memories based on atomic resonances that have narrow linewidths.

Typically biphoton entanglement exhibits entanglement in the time of creation between the two photons with anti-correlation between the frequencies of the two photons. We demonstrated biphoton entanglement in which the two photons have the same frequencies, hence anti-correlated in their times of arrival. By utilizing extended phase-matching [17, 18], in which there is zero group-velocity mismatch in the nonlinear crystal, coincident-frequency entanglement was demonstrated in PPKTP under pulsed pumping with a pulse width of 300 fs. This source produced biphotons with 1.3 ps coherence times [19]. The long biphoton coherence time, compared with the pump pulse width, indicated correlation times beyond what classical limits allow and thus was a manifestation of frequency entanglement. We utilized this extended phase-matching, pulsed-pumped downconverter to demonstrate a high-quality Hong-Ou-Mandel dip. Unlike all previous pulse-pumped experiments of this type, ours did not require narrowband filtering of the output light to produce high-quality quantum interference.

$\chi^{(3)}$ Sources

We developed fiber-based sources of quadrature as well as polarization entanglement. Experiments were conducted in both the 800 nm and the 1500 nm portions of the electromagnetic spectrum. In the former case the experiments were done using microstructure fibers (MFs), also known as holey or photonic-crystal fibers, whereas in the latter case both conventional fibers as well as MFs were used. Below we describe our main accomplishments in these $\chi^{(3)}$-source developments .

We implemented a polarization Mach-Zehnder interferometer that can be configured either as an asymmetric or a symmetric Sagnac loop. This configuration allowed us to obtain amplitude-squeezed soliton-like pulses with highly asymmetric setting of the beam splitters and squeezed-vacuum pulses with symmetric setting. Our apparatus yielded higher squeezing values than ever reported from a fiber-based device. A detailed experimental study of the generation of amplitude-squeezed soliton-like pulses was carried out with the interferometer containing standard polarization maintaining (PM) fiber [24]. Up to 4.4 dB of squeezing was directly observed, corresponding to 6.6 dB when the degradation due to losses external to the fiber was accounted for. Although the fiber-length dependence was in reasonable agreement with the quantum theory of soliton propagation in the fiber, the 6.6 dB value was considerably less than the >10 dB value predicted by the theory. Also, better squeezing was obtained with pulses that had peak powers roughly 50% higher than the soliton power. In order to account for these observations, we also undertook a detailed theoretical study of squeezing generation in our experiment [25]. Our study was based on the linearization approximation, in which the linearized quantum nonlinear Schroedinger equation is numerically solved. The novelty in our modeling is the inclusion of linear loss in the fiber, which is not negligible when MF is used [26]. Although the results of the numerical modeling correctly predict the experimental observation of larger squeezing at higher pulse peak powers than the soliton power, the predicted maximum-squeezing magnitude was still considerably larger than that observed in the experiment. We believe this discrepancy might be due to the Raman effect, which was not included in the theoretical model, but is significant for the 180 fs pulses used in our experiment.

To develop fiber-optic sources of polarization-entangled photon pairs, we conducted nondegenerate four-wave mixing experiments in dispersion-shifted fibers (DSFs) as well as MFs. To demonstrate the quantum nature of the four-photon scattering (FPS) process at the "single" photon level, that is, two pump photons scattering through the Kerr nonlinearity to create simultaneous signal and idler photons, we implemented novel pulsed coincident-counting schemes [27] with the goal of demonstrating fourth-order interference as well as violation of Bell's inequalities in the fiber systems. We worked side-by-side on two different fronts. The first was geared towards obtaining entangled photon pairs in the 1550 nm low-loss transmission window of the standard fiber, whereas the second used MFs for obtaining the photon pairs in the 800 nm region in order for it to be compatible with the rubidium-based quantum memory. Both experiments were based on nondegenerate four-photon scattering near the zero-dispersion wavelength of the fiber, where the cross-section for such interaction is enhanced owing to phase matching of the photon wave functions.

In our 1550-nm experiments, we first observed twin-photon beams with external injection of signal photons to stimulate the four-photon scattering process. The resulting amplified signal photons and the generated idler photons showed sub-shot-noise quantum correlations in direct detection [28]. We further demonstrated for the first time the quantum nature of the four-photon scattering process at the "single" photon level by detecting the signal and idler photons in coincidence [29]. Because of the isotropic nature of the Kerr nonlinearity in fused-silica-glass fiber, the scattered, correlated photon-pairs are predominantly co-polarized with the pump photons in the scattering process. By coherently adding two such orthogonally-polarized FPS processes, we also demonstrated the generation of polarization entanglement [30]. Bells inequalities were violated by up to 10 standard deviations of measurement uncertainty in these experiments and all four Bell states could be produced in the setup. Using such a fiber-based source, we then proceeded to demonstrate the storage of one photon of the pair in a 25 km loop of fiber while maintaining entanglement with the other and the long-distance distribution of polarization entanglement over 50 km of standard single-mode fiber with negligible decoherence of the entangled photon pairs [31]. This experiment demonstrated for the first time the viability of all-fiber sources for use in quantum memories and quantum logic gates. This fiber-based approach to photon-pair generation has been followed in many laboratories around the world. Northwestern University also applied and received a patent on this method of generating correlated and entangled photon-pairs in the telecom band and in the visible region using microstructure fiber [32].

In the early experiments, the ratio of the true coincidence counts to accidental coincidence counts was quite low due to the presence of background photons. A study of the cause of these background photons pointed the finger to the Raman effect, which is invariably present owing to its connection with the imaginary part of the same Kerr nonlinearity whose real part gives rise to the four-photon correlation [33, 34, 35]. By carefully optimizing the experimental parameters, we were able to consistently achieve ratios higher than ten [36]. Our work towards the end of the project focused on characterizing the fidelity of the fiber-based entangled photon sources. As noted above, the presence of Raman scattering in fibers sets the ultimate limits on the quality of two-photon entanglement that can be produced from fibers. In order to determine the limiting fidelity, as characterized by the visibility of two-photon interference fringes, we made extensive measurements of the spectra of the co- and cross-polarized Raman scattering in standard dispersion-shifted fiber for small detunings. We were able to make precise measurements of the Raman-gain spectra on both the Stokes and anti-Stokes sides because of our use of a photon-counting technique. Furthermore, the use of a pulsed pump eliminated Brillouin scattering and the use of a fiber Sagnac loop suppressed self-phase-modulation (SPM) induced spectral broadening from contaminating the measurements, thus enabling us to make precise measurement of the Raman gain down to a detuning of 0.17 THz from the pump [37].

We also developed a quantum theory for the pulsed four-photon interaction in the nonlinear fiber without inclusion of the Raman effect. In this theory, the pump is treated as a classical picosecond-duration pulse due to its experimental relevance. The signal and idler fields form a quantum mechanical two-photon (or "biphoton") state with spectra that are specified by the filters placed in front of the detectors. Our goal was to study the dependence of the generation efficiency of the correlated photon pairs on various system parameters, including the shape of the pump pulse shape and the width of the filters placed in front of the detectors. Numerical predictions from the theory were shown to be in good agreement with the experimental results [38, 39].

We also constructed and characterized several versions of portable, telecom-band entangled-photon sources. Using a palm-sized femtosecond mode-locked fiber laser producing 100 fs pulses in the telecom band we constructed two portable entangled-photon sources, one based on the Sagnac-loop scheme used in our earlier experiments and the other using a counter-propagating scheme that directly yields polarization-entangled photons [40]. In both cases, highly-compact fiber-Bragg gratings and fiber-connected thin-film filters were used to obtain the required >100 dB rejection of the pump photons. Both sources are capable of being packaged into 18-inch rack-mountable boxes. In two-photon interference experiments, entangled photons from both sources yielded $> 0\%$ fringe visibilities without subtracting the Raman background [41]. Our experiments towards the end of the program indicate that up to 98% visibility is possible by cooling the fiber to liquid nitrogen temperatures.

In the 800-nm region we undertook detailed studies of four-wave mixing using the microstructure (holey) fiber obtained from Lucent [42]. We believe this was the first time four-wave mixing had been observed in such novel-structure fibers. For creating polarization-entangled photon pairs in the 800 nm region, most of our early effort was focused on understanding the classical nonlinear optics in MFs. This work was also part of the MURI Fellow funding for Jay Sharping. We reported a detailed study of our observation of four-wave mixing with >13 dB gain in the 750-nm-wavelength region using the MF obtained from Lucent [40]. In addition, we used the very efficient cross-phase modulation effect in MFs to demonstrate all-optical switching [43]. This work is relevant for advancing the state-of-the-art in classical all-optical communications and for implementing advanced fiber-optic communication networks. We also conducted experiments with MFs to demonstrate a four-wave-mixing oscillator, with an eye towards implementing our experiments in the continuous-wave regime for compatibility with the rubidium-based quantum memory [44]. Once the MF had been thoroughly characterized classically, we undertook experiments to demonstrate the generation of correlated photon pairs in the 800-nm region. These experiments suffered from high photon losses because the input and output coupling to the MF had to be done with free-space optics, as opposed to spliced connections in the 1500 nm experiments. Nevertheless, we were able to observe for the first time the generation of correlated photon pairs in the 800 nm band [45].

Quantum-State Frequency Conversion

The MIT-NU architecture requires that fiber-delivered photons at 1.55–1.6 μm wavelength be upconverted to the 795 nm wavelength of the Rb-atom memory with high efficiency and in a manner that preserves their polarization state. An efficient quantum-state frequency converter would also be useful for increasing the single-photon counting efficiency at near-infrared wavelengths. During our program we developed highly-efficient upconverters using both continuous-wave pumping of bulk nonlinear crystals and pulsed pumping of nonlinear-crystal waveguides. In particular, in our bulk-crystal experiments we demonstrated 90%-efficient frequency upconversion from 1550 nm to 633 nm at the single-photon level [46]. Sum-frequency generation in bulk PPLN using a strong pump at 1064 nm in a ring cavity converted input single photons at 1550 nm to output single photons at 633 nm. Polarization-insensitive upconversion was also demonstrated [47], in continuous-wave pumped bulk PPLN, that can be used to provide frequency translation with the quantum-state preservation for long-distance quantum communication. In our pulse-pumped waveguide experiment we demonstrated the first photon-counting measurements that reached a conversion efficiency of 100% within the waveguide [48].

Atomic Systems for Quantum Memory

Trapped-Atom Quantum Memory

In pursuit of the goal of demonstrating the MIT/NU architecture for long distance quantum teleportation [3], we developed two far-off-resonance traps integrated with high-Q optical cavities (cavity-FORT systems) loaded with rubidium atoms launched from magneto-optical traps (MOTs) [14]. Unfortunately, we fell short of achieving the goal of trapping single atoms. Nevertheless, the apparatus we developed is likely to be useful in continued pursuit of similar experiments in the field of quantum information processing. Specifically, these two cavity-FORT systems are sufficiently versatile to explore a range of different experiments, by varying the number of atoms that are caught in the trap. Toward that end we developed two separate MOT chambers, each loaded with a chirp-slowed thermal Rb atomic beam. In each chamber, the atoms caught in the MOT are pushed vertically using a launch beam. In one chamber, the launched atoms are guided using a quadrupolar magnetic wire-guide. A high-Q, standing wave cavity was placed at this location, and stabilized to an atomic resonance using a 50% duty-cycle probe. For capturing the atoms, we used a FORT beam from a separate Ti-Sapphire laser. In the other chamber, we constructed a cavity system consisting of two intersecting traveling-wave (ring) resonators, each with a relatively low finesse (about 100). The intersection point also coincides with the location of the FORT. This was designed to demonstrate a quantum nondemolition single-photon detector using the extremely high Kerr nonlinearity that is predicted to occur under electromagnetically-induced-transparency (EIT) conditions in an atomic ensemble. Furthermore, either cavity by itself can also be used to test the light-shift imbalance induced blockade in ensemble excitation described below.

Off-Resonant Raman Quantum Memory

Recently, ensemble based quantum memory has been demonstrated using EIT, which employs optically resonant Raman excitation. This memory is inherently lossy, due to the fact that the photon pulse has a finite bandwidth, and the inherent absorption at frequencies away from the exact EIT condition leads to spectrally-dependent losses in the photon. The result is a loss of fidelity as well as distortion of the spatio-temporal profile of the photon to be stored and recalled. We have pursued the development of a more robust ensemble quantum memory, employing off-resonant Raman excitation. This process is generally not employed due to the fact that one cannot employ a vapor-cell-based, narrowband, high-extinction filter to isolate the strong pump from the weak probe. However, we found [50, 51] that if ^{85}Rb is used for the optically off-resonant Raman memory, then the pump can be resonant with a transition in ^{87}Rb, so that a ^{87}Rb vapor cell can be used for efficient isolation of the pump.

In our experiments, we initially used vapor cells made with the naturally occurring mixture of Rb isotopes. The Raman gain was studied using self-pumping as well as external optical pumping. In the presence of an external probe, the gain was observed to have a single peak, as expected. However, when spontaneous Raman scattering was observed using a photon counter, several different peaks were observed [51]. Our theoretical analysis showed that these lines resulted from light shifts of the hyperfine sublevels of both isotopes. The presence of such a multiplicity of peaks in the Raman scattering is expected to reduce the fidelity of a quantum memory that is based on such a system. As such, we next chose to operate under conditions where the light shifts were suppressed. Furthermore, we obtained vapor cells made from pure Rb isotopes. As a result, we were able to observe again just a single peak for the Raman scattering, as needed for the quantum memory application.

In order to demonstrate quantum memory operation in a deterministic manner, we used a source of entangled photon pairs developed in our program. When pumped by a laser operating at 532 nm, this source produces pairs of photons, one of which is at 795 nm while the other is around 1608 nm. The photon at 795 nm was to be captured by the Rb-cell quantum memory, prepared to be in the read mode using optical pumping as well as a Raman pump. Subsequently, the photon was to be retrieved by applying a Raman read-out pulse, and recorded with a photon counter. The other photon was to be detected with a second photon counting system based on an InGaAs photodiode. Using electronic delay, the coincidence rate between these two processes can be determined, and compared with the corresponding coincidence rate when both photons are detected directly, without the quantum memory. The entangled-photon source had a very broad bandwidth. As such, the number of photons within the narrow Raman absorption bandwidth of Rb vapor was very small. In order for this approach to work well, it was necessary to filter the photons at 1608 nm with a Fabry-Perot filter as narrow as the vapor cell. Furthermore, this filter had to remain locked at the precise frequency at which the correlation is maximum. This can be done, for example, by using a super-stable, tunable, distributed-feedback stabilized laser of the type typically employed in testing DWDM communication system. Work on this quantum memory was not completed under our MURI program, but it is being continued under subsequent DARPA funding. We expect to realize such the necessary filtering and demonstrate the direct storage and recall of photons produced by the entangled-photon source.

As a more immediate alternative, we tested the quantum memory using a weak coherent-state source. The photon statistics of an attenuated coherent state were first established experimentally. The same beam was then stored in the quantum memory. Because the memory's capture rate depends on the number of photons it captures, the statistics of the attenuated coherent state—after passing through the quantum memory for a given time interval—get altered in a well-defined way. The predicted photon statistics were then compared with the experimental results in order to determine how well the quantum memory was working. Similarly, the photon statistics of the quantum memory's output, once the captured photons were released—again at different rates—were compared with the theoretical predictions in order to establish the fidelity of the quantum memory. We obtained preliminary results for this sequence of experiments, and further optimization is underway to achieve the high fidelity expected from this device. This work too is continuing beyond the MURI program under DARPA funding.

Atomic Ensembles as Qubits

In addition to its use as a deterministic quantum memory, an optically-pumped vapor cell can be used for generating macroscopic entanglement, which in turn may be used in a quantum repeater or in quantum teleportation, provided that the condition for collective excitation is satisfied. However, unlike the quantum memory, the quantum repeater or quantum teleportation functions that are realized this way are not deterministic. This is because multi-photon processes are not forbidden. It has previously been realized that use of inter-atom dipole-blockade, for example, can suppress multi-photon processes, and render the system deterministic. However, given that the inter-atomic separations are randomly distributed, and the dipole-blockade depends on this separation, this approach is not likely to work for a vapor cell, nor for trapped atoms. We have devised a different mechanism for blockade that is uniform for all the atoms, via the process of light-shift imbalance [52, 53, 54, 55]. This process makes atomic-ensemble based quantum repeater and quantum teleportation operations into deterministic functions [53]. Furthermore, we have shown that this process can be used to realize a deterministic quantum bit based on atomic ensembles, and have shown explicit steps for realizing a CNOT gate between two such qubits [53]. Efforts are underway to test this mechanism using a trapped ensemble and a low-Q cavity, as described later on. Realization of this technology would provide a potentially simpler alternative for implementing a quantum Internet [56].

Additional Research

Single-Photon, Two-Qubit Quantum Logic

By utilizing both the polarization and momentum degrees of freedom of single photons as independent qubits, we demonstrated a polarization-controlled NOT (P-CNOT) gate [57], a momentum-controlled NOT (M-CNOT) gate, and a SWAP gate [58] that, together with single-qubit rotation using wave plates, form a universal gate set for single-photon two-qubit (SPTQ) quantum logic. SPTQ quantum logic can be used for manipulating qubits of hyperentangled photons and for enhancing quantum information processing tasks. We showed [59] that SPTQ quantum logic can be used to perform a complete physical simulation of the most powerful individual attack on Bennett-Brassard 1984 quantum key distribution, viz., the Fuchs-Peres-Brandt probe. Under DARPA funding we are now setting up an experiment to perform that simulation.

Quantum-Enhanced Precision Measurements and Communication

In theoretical work we showed that entanglement may be used to improve precision measurement, timing, and positioning [60]–[65]. We also demonstrated that entanglement could play a role in enhancing the power-limited capacity of communication channels in particular, and of dynamical evolution in general [66, 67, 68]. In studying applications for our techniques to distribute entanglement, we were led to our collaboration with Peter Shor on the entanglement-assisted capacity of Bosonic channels [69, 70].

By applying the fundamental physics of information processing, we were able to derive a series of results on the computational and communication capacity of physical systems [71]–[76]. This work included deriving fundamental limits to the accuracy with which measurement can take place, including measurement of space and time.

Capacity of Bosonic Communications

A principal goal of quantum information theory is evaluating the information capacities of important communication channels. At present, exact capacity results are known for only a handful of channels. We have considered the classical capacity C of Bosonic channels with isotropic Gaussian noise. This study connects to a research line that began with the capacity derivation for the lossless (and hence noiseless) Bosonic channel [77, 78], and only very recently led to our deriving the capacity of the pure-loss Bosonic channel [79]. For that channel, we have the exact values of C for single-mode operation under an average photon-number constraint at the input, and for wideband operation under an average power constraint at the input. In both cases quantum entanglement is not necessary to achieve capacity, and "classical" encoding procedures employing coherent states suffice. This means that the Holevo information of the pure-loss channel is additive. Moreover, at high average powers we have shown that heterodyne detection is asymptotically optimum for single-mode operation and for far-field, free-space communication. For active channel models—in which noise photons are injected from an external environment or the signal is amplified with unavoidable quantum noise—we have obtained upper and lower bounds for the capacity, which are asymptotically tight at low and high noise levels. Exact results for these active channels would follow from proving the conjecture that a coherent-state input minimizes the output entropy from such channels [80, 81]. In other channel capacity work we derived the first results for the multiple-access capacity region of Bosonic channels [82], and we established the limit on channel capacity when orbital angular momentum spatial modes are employed in free-space propagation Bosonic communications [83].

Quantum Information Security and Processing

We created a protocol for anonymous key identification [84], which involves the use of quantum states for unconditionally secure agent identification.

In [85, 86], we showed why there is no impossibility proof for unconditionally secure quantum bit commitment. Protocol QBC1 in [86] and protocol QBC5 in [87] are indeed unconditionally secure. They will be rewritten in more understandable form for journal publication.

In [88] we showed that entanglement purification is much harder to achieve for continuous-variable teleportation compared to qubit teleportation. However, the comparison is not entirely general and there are also possibilities of using a whole infinite-dimensional space as a qubit. We have not, however, explored such avenues.

We found that the protocol of Ambanis, Smith and Yang is the only one in the literature that may be applicable to a real experimental system. It is still, however, too idealized and limited in capability. On the other hand, it may make possible a demonstration of some simple entanglement enhancement using just CNOT gates.

References

[1] For ease of calculation, without appreciable loss of generality, our architectural analysis relies on a symmetric arrangement, wherein the entanglement source is

equidistant from the two trapped-atom memories. In actual implementation the source will be co-located with one of these quantum memories.

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